ZOOM LENS AND PROJECTION
DISPLAY DEVICE WHICH USES SAME

BACKGROUND OF THE INVENTION

Zoom lenses of a five-group construction are known. For example, Japanese Laid-Open Patent Application 2000-292701, and Japanese Laid-Open Patent Application 2001-004919 disclose zoom lenses that include, in order from the enlarging side, a first lens group having

5   negative refractive power and a focusing function and that is stationary during zooming, a second lens group having positive refractive power, a third lens group having positive refractive power, a fourth lens group having negative refractive power, with the second, third, and fourth lens groups being movable for zooming, and a fifth lens group having positive refractive power that is fixed during zooming.

10   There has been a demand for a zoom lens of the type described in these Japanese published applications that provides a bright image even with a liquid crystal image source in a projection display device and that has the compactness desired in a projection display device. Additionally, it is desirable that the zoom lens be at least nearly telecentric on the reducing side and includes a large enough back focus distance to provide room for a color synthesizing optical

15   system in a projection display device or, similarly, a color separation optical system when the zoom lens is used in a camera.

Furthermore, recently there has been a demand for projection to a large screen at a close distance by using a projection lens with an even wider field angle. For example, it is desirable to be able to project an image that is up to one hundred inches across with a projection distance of

20   only 2.5 to three meters in projection display devices as described in the Japanese applications discussed above. Moreover, a larger zoom ratio has been desired in order to obtain this size image and to vary the size of the projected image.

However, with the increased use of projection display devices, the devices are not necessarily desirably placed directly between a screen and an audience, thus more freedom in

25   placement is desired. For example, it may be desirable to hang the projection display device from the ceiling behind the audience and project an image over the heads of the people in the

audience onto a screen. In this case, a zoom lens with a long focal length and that is telecentric on the reducing side is preferred for projecting the image, and when projecting to a one hundred inch image size as described above, a zoom lens designed for favorable optical performance with a projection distance of five to ten meters is required.

BRIEF SUMMARY OF THE INVENTION

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The present invention relates to a zoom lens that includes five lens groups, three of which move for zooming, provides a long focal length, is telecentric on the reducing side, favorably corrects various aberrations, and is suitable for use in a projection display device that uses a liquid crystal as an image source . Additionally, the present invention relates to a projection

10 display device, such as a projection television, that uses such a zoom lens with a liquid crystal image source, or similar image source, and to a camera that uses an image pickup element, such as a CCD, an image pickup tube, photographic film, or a similar structure.

BRIEF DESCRIPTION OF THE DRAWINGS

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The present invention will become more fully understood from the detailed description given below and the accompanying drawings, which are given by way of illustration only and thus are not limitative of the present invention, wherein:

Fig. 1 shows cross-sectional views of the zoom lens of Embodiment 1 at the wide-angle end (WIDE) and the telephoto end (TELE);

20 Fig. 2 shows cross-sectional views of the zoom lens of Embodiment 3 at the wide-angle end (WIDE) and the telephoto end (TELE);

Figs. 3A - 3D show aberrations of the zoom lens of Embodiment 1 at the wide-angle end;

Figs. 3E - 3H show aberrations of the zoom lens of Embodiment 1 at an intermediate position;

25 Figs. 3I - 3L show aberrations of the zoom lens of Embodiment 1 at the telephoto end;

Figs. 4A - 4D show aberrations of the zoom lens of Embodiment 2 at the wide-angle end;

Figs. 4E - 4H show aberrations of the zoom lens of Embodiment 2 at an intermediate

position;

        Figs. 4I - 4L show aberrations of the zoom lens of Embodiment 2 at the telephoto end;

        Figs. 5A - 5D show aberrations of the zoom lens of Embodiment 3 at the wide-angle end;

        Figs. 5E - 5H show aberrations of the zoom lens of Embodiment 3 at an intermediate

5   position;

        Figs. 5I - 5L show aberrations of the zoom lens of Embodiment 3 at the telephoto end;

        Figs. 6A - 6D show aberrations of the zoom lens of Embodiment 4 at the wide-angle end;

        Figs. 6E - 6H show aberrations of the zoom lens of Embodiment 4 at an intermediate

position;

10   Figs. 6I - 6L show aberrations of the zoom lens of Embodiment 4 at the telephoto end;

and

        Fig. 7 shows a schematic representation of a projection display device in which a zoom

lens of the present invention may be used.

DETAILED DESCRIPTION

15   A general description of the preferred embodiments of the zoom lens of the present

invention will now be described with reference to Fig. 1 that shows Embodiment 1. In Fig. 1,

lens groups are referenced by the letter G followed by a number denoting their order from the

enlarging side of the zoom lens, from G_1 to G_5, along the optical axis X. Lens elements are

referenced by the letter L followed by a number denoting their order from the enlarging side of

20   the zoom lens, from L_1 to L_{14} for Embodiments 1 - 4 that follow. In Embodiments 1 - 4, as

shown in Figs. 1 and 2, an upper left arrow points toward the enlarging side and an upper right

arrow points toward the reducing side. In Figs. 1 and 2, reference numeral 2 denotes a color

synthesizing optical system, such as a color synthesizing prism, as well as an infrared cut-off

filter or a low-pass filter that may be present. When the zoom lens is used in a camera, reference

25   numeral 2 would relate to a color separating optical system. Reference numeral 1 denotes a

liquid crystal display panel that serves as an image source when the zoom lens is used to project

images onto a screen (not illustrated) positioned on the enlarging side. Radii of curvature of the

optical surfaces of all the optical elements are referenced by the letter R followed by a number

denoting their order from the enlarging side of the zoom lens, from R_1 to R_{27} in Fig. 1 and from

R_1 to R_{28} in Fig. 2. The on-axis surface spacings along the optical axis X of all the optical

element surfaces are referenced by the letter D followed by a number denoting their order from

5   the enlarging side of the zoom lens, from D_1 to D_{26} in Fig. 1 and from D_1 to D_{27} in Fig. 2. The

top parts of Figs. 1 and 2 show the positions of the five lens groups at the wide-angle end,

indicated by symbol "WIDE," and the bottom parts of Figs. 1 and 2 show the positions of the five

lens groups at the telephoto end, indicated by the symbol "TELE."

        The term "lens group" is defined in terms of "lens elements" and "lens components" as

10   explained herein. The term "lens element" is herein defined as a single transparent mass of

refractive material having two opposed refracting surfaces, which surfaces are positioned at least

generally transversely of the optical axis of the zoom lens. The term "lens component" is herein

defined as (a) a single lens element spaced so far from any adjacent lens element that the spacing

cannot be neglected in computing the optical image forming properties of the lens elements or (b)

15   two or more lens elements that have their adjacent lens surfaces either in full overall contact or

overall so close together that the spacings between adjacent lens surfaces of the different lens

elements are so small that the spacings can be neglected in computing the optical image forming

properties of the two or more lens elements. Thus, some lens elements may also be lens

components. Therefore, the terms "lens element" and "lens component" should not be taken as

20   mutually exclusive terms. In fact, the terms may frequently be used to describe a single lens

element in accordance with part (a) above of the definition of a "lens component."

        The term "lens group" is used herein to define an assembly of one or more lens

components in optical series and with no intervening lens components along an optical axis that

during zooming is movable as a single unit relative to other lens components. Thus, for example,

25   in a zoom lens, a lens group may be stationary or movable with respect to an image plane of the

lens group, and stationary lens elements of the zoom lens may define different lens groups based

on those different lens groups being separated by lens groups that move relative to those different

lens groups and the image plane. More specifically as an example, a lens group at the enlarging

end and a lens group at the reducing end of a zoom lens may be stationary, but they are not part of the same lens group because they are separated by other lens components that belong to other lens groups.

As shown in Fig. 1, a zoom lens according to the present invention includes, in order from the enlarging side, a first lens group G_1 of negative refractive power that is moved along an optical axis X for focusing but that is stationary during zooming, a second lens group G_2 of positive refractive power, a third lens group G_3 of negative refractive power, a fourth lens group G_4 of negative refractive power, and a fifth lens group G_5 of positive refractive power that operates as a relay lens and that is stationary during focusing and zooming. Lens groups G_2, G_3, and G_4 move continuously during zooming from the wide-angle end to the telephoto end in order to provide zooming and adjustment of the image plane due to zooming. It is preferable that the second lens group G_2 move toward the enlarging side and the fourth lens group G_4 move toward the reducing side, that is, away from the enlarging side, during zooming from the wide-angle end to the telephoto end of the zoom range.

Preferably, the following condition is satisfied:

$$-2.2 < F1 / F < -1.2 \qquad \ldots \text{Condition (1)}$$

where

F1 is the focal length of the first lens group G_1, and

F is the focal length of the zoom lens at the wide-angle end when the zoom lens is focused at infinity on the enlarging side.

Also, the following condition is preferably satisfied:

$$0.6 < F2 / F < 1.1 \qquad \ldots \text{Condition (2)}$$

where

F2 is the focal length of the second lens group G_2, and

F is as defined above.

Additionally, the following condition is preferably satisfied:

$$-15.0 < F4 / F < -1.5 \qquad \ldots \text{Condition (3)}$$

where

5

F4 is the focal length of the fourth lens group G_4, and

F is as defined above.

Furthermore, preferably the following condition is satisfied:

$$0.7 < F5 / F < 1.2 \qquad \dots \text{Condition (4)}$$

where

F5 is the focal length of the fifth lens group G_5, and

F is as defined above.

If the lower limit of Condition (1) is not satisfied, correction of aberrations of the zoom lens due to the small f-number becomes difficult, and the negative refractive power of the first lens group G_1 becomes so weak that much movement of the first lens group G_1 is required for focusing, resulting in large fluctuations in the aberrations. On the other hand, if the upper limit of Condition (1) is not satisfied, the negative refractive power of the first lens group G_1 becomes strong and axial light rays are diverged so far from the optical axis by the first lens group G_1 that correction of aberrations, especially distortion and spherical aberration, becomes difficult.

If the lower limit of Condition (2) is not satisfied, the positive refractive power of the second lens group G_2 becomes so large that correction of aberrations becomes difficult. On the other hand, if the upper limit of Condition (2) is not satisfied, the positive refractive power of the second lens group G_2 becomes so weak that the required movement of the second lens group G_2 that moves during zooming becomes too large, making the zoom lens itself too large.

If the lower limit of Condition (3) is not satisfied, the negative refractive power of the fourth lens group G_4 is so weak that so much movement of the fourth lens group G_4 is required for the desired zooming that it is difficult to make the zoom lens compact. On the other hand, if the upper limit of Condition (3) is not satisfied, the negative refractive power of the fourth lens group G_4 is so strong that aberrations become difficult to correct.

Among the two negative refractive power lens groups G_3 and G_4 in the moving lens groups G_2 - G_4, if one lens group has strong refractive power and the other has weak refractive power, this results in the amount of movement of the lens group with weak refractive power

increasing, making miniaturization more difficult. If miniaturization is to be achieved in this situation, the burden increases on the other lens groups with regard to correction of aberrations. As a result, the correction of aberrations becomes difficult. Thus, it is preferred that the negative refractive power be allotted in a balanced manner among the lens groups G_3 and G_4 so that the

5   light flux is gradually diverged.

If the lower limit of Condition (4) is not satisfied, the back focal length of the zoom lens becomes so short that obtaining a nearly telecentric state on the reducing side becomes very difficult. Also, there is insufficient space for inserting a dichroic prism such as glass block 2 in Fig. 2, for example, which provides the color synthesis necessary to project color images. On

10   other hand, if the upper limit of Condition (4) is not satisfied, the back focus becomes too long and the correction of aberrations becomes more difficult.

In order to realize a zoom lens that is telecentric on the reducing side, the negative refractive power must be made stronger in comparison to a standard zoom lens. However, when doing so by changing the power balance between the first lens group G_1 for performing focusing

15   and the fixed fifth lens group G_5, there is a significant reduction in optical performance. In order to obtain favorable optical performance, the change to the power balance is preferably resolved in the moving groups of G_2 through G_4. However, even within the moving lens groups G_2 through G_4, making the refractive power of the lens group or groups having negative refractive power to be too strong or making the refractive power of the lens group or groups having positive

20   refractive power to be too weak is not desirable for optical performance. Therefore, the zoom lens of the present invention separates the negative refractive power into two lens groups, the third lens group G_3 and the fourth lens group G_4, with neither of these lens groups having too much of the refractive power.

Moreover, since the first lens group G_1 diverges light rays generally based on the first lens

25   group having negative refractive power, it is preferred that from among the moving lens groups G_2 through G_4, the second lens group G_2 be the lens group that has positive refractive power and the negative refractive power be divided between the third lens group G_3 and the fourth lens group G_4. By having three groups G_2 through G_4 move during zooming, a nearly telecentric state

can be maintained during zooming.

Furthermore, in the zoom lens of the present invention, the second lens group G_2 moves toward the enlarging side during zooming from the wide-angle end to the telephoto end, and the fourth lens group G_4 is positioned nearer the reducing side when at the telephoto end than when

5   at the wide-angle end. Because the height of an axial light ray in the second lens group G_2 is larger at the telephoto end than at the wide-angle end, the diameters of the lens elements of the second lens group G_2 can be made to be smaller if the second lens group G_2 is nearer the enlarging side at the telephoto end than at the wide-angle end.

With regard to the fourth lens group G_4, having the fourth lens group G_4 nearer the

10   reducing side at the telephoto end of zooming than at the wide-angle end of zooming helps reduce the diameters of the lens elements of the first lens group G_1 and the second lens group G_2. In the zoom lens of the present invention, the effective stop position where an off-axis axial light ray intersects the optical axis depends largely on the refractive power of the fifth lens group G_5. At the wide-angle end of zooming, the effective stop position is roughly in the vicinity of the

15   third lens group G_3 and the fourth lens group G_4. For example, in Embodiments 1- 4 of the present invention described below, the effective stop position is between the third lens group G_3 and the fourth lens group G_4. If the lens group G_4 is moved too far toward the enlarging side during zooming from the wide-angle end to the telephoto end, it may be positioned at the enlarging side of the effective stop position at the telephoto end. The light rays including the

20   peripheral light flux that is essential to providing a bright image are diverged far from the optical axis by the third lens group G_3 and the fourth lens group G_4, each of which has negative refractive power. As a result, these light rays pass far away from the optical axis in the first lens group G_1 and the second lens group G_2, and this makes it difficult to make the diameters of the lens groups G_1 and G_2 small. By moving the fourth lens group G_4 toward the reducing side

25   during zooming from the wide-angle end to the telephoto end, the lens elements of lens groups G_1 and G_2 can be made with small diameters, thus providing compactness while achieving sufficient image brightness by assuring that the effective stop position remains between the lens groups G_3 and G_4.

Embodiments 1 - 4 of the present invention will now be individually described with

30   reference to the drawings.

Embodiment 1

Fig. 1 shows the basic lens element configuration of the five-group zoom lens of Embodiment 1. In Embodiment 1, the first lens group G_1 includes, in order from the enlarging side: a first lens element L_1 that is biconvex with surfaces of different curvature and with its

5   surface of lesser curvature on the reducing side intimately bonded to a second lens element L_2 that is biconcave with surfaces of different curvature and with its surface of greater curvature on the reducing side; a third lens element L_3 that is a biconcave lens element having surfaces of different curvature and with its surface of greater curvature on the reducing side; and a fourth lens element L_4 of positive refractive power and a meniscus shape with its convex surface on the

10   enlarging side.

The second lens group G_2 includes, in order from the enlarging side: a fifth lens element L_5 that is biconvex with surfaces of different curvature and with its surface of greater curvature on the reducing side; and a sixth lens element L_6 that is biconvex with surfaces of different curvature and with its surface of greater curvature on the enlarging side.

15   The third lens group G_3 includes, in order from the enlarging side: a lens component formed of a seventh lens element L_7 that is biconvex with surfaces of the same curvature and with its surface on the reducing side intimately bonded to an eight lens element L_8 that is biconcave with surfaces of different curvature and with its surface of greater curvature on the reducing side.

20   The fourth lens group G_4 includes, in order from the enlarging side: a ninth lens element L_9 that is biconcave with surfaces of the same curvature and with its surface on the reducing side intimately bonded to the tenth lens element L_{10} of positive refractive power and a meniscus shape with is convex surface on the enlarging side.

The fifth lens group G_5 includes, in order from the enlarging side: an eleventh lens

25   element L_{11} that is biconcave with surfaces of different curvature and with its surface of greater curvature on the enlarging side; a twelfth lens element L_{12} of positive refractive power and a meniscus shape with its convex surface on the reducing side; a thirteenth lens element L_{13} that is biconvex with surfaces of different curvature and with its surface of greater curvature on the

enlarging side; and a fourteenth lens element L_{14} that is plano-convex with its convex surface on the enlarging side.

The term "intimately bonded" is defined herein generally to mean that adjacent refractive surfaces of two lens elements have substantially the same curvature and are held in direct fixed

5   contact or are separated by a thin layer of transparent adhesive (too thin to be considered in optical computations) that fixes the lens elements together, the latter being commonly referred to as a "cemented" lens element arrangement.

As shown in Fig. 1, the second lens group G_2 and the third lens group G_3 move toward the enlarging side during zooming from the wide-angle end to the telephoto end, while the fourth

10   lens group G_4 moves toward the reducing side during zooming from the wide-angle end to the telephoto end.

Table 1 below lists the surface number #, in order from the enlarging side, the radius of curvature R of each surface, the on-axis surface spacing D, as well as the refractive index N_d and the Abbe number v_d (both at the d-line) of each lens element for Embodiment 1. The numerical

15   values of R and D are based on a normalized focal length of unity at the wide-angle end of the zoom lens of Embodiment 1 (i.e., with the zoom lens focused at infinity). The zoom lens of Embodiment 1 provides a reducing magnification of -0.0098 at the image reducing side at the wide-angle end of the zoom lens.

TABLE 1

#	R	D	N_d	ν_d
1	1.253	0.180	1.83400	37.2
2	-43.225	0.041	1.56384	60.7
3	0.764	0.403		
4	-1.335	0.038	1.62299	58.2
5	0.995	0.044		
6	1.088	0.060	1.83400	37.2
7	2.468	D_7 (variable)		
8	3.415	0.064	1.80400	46.6
9	-2.568	0.064		
10	1.867	0.100	1.80400	46.6
11	-5.769	D_{11} (variable)		
12	1.021	0.207	1.80400	46.6
13	-1.021	0.032	1.84666	23.8
14	0.791	D_{14} (variable)		
15	-1.002	0.029	1.48749	70.2
16	1.002	0.050	1.80610	40.9
17	2.345	D_{17} (variable)		
18	-1.135	0.035	1.51742	52.4
19	1.707	0.039		
20	-5.159	0.081	1.61800	63.3
21	-0.882	0.005		
22	1.411	0.094	1.77250	49.6
23	-3.405	0.167		
24	1.448	0.081	1.71300	53.9
25	∞	0.117		
26	∞	0.549	1.51633	64.1
27	∞			

In the zoom lens of Embodiment 1, lens groups G_2, G_3, and G_4 move to vary the separations of the five lens groups during zooming. Therefore, the values of the on-axis spacings D_7, D_{11}, D_{14} and D_{17} vary.

Table 2 below lists the values of the variables D_7, D_{11}, D_{14} and D_{17} (i.e., the group spacings) at zoom ratios of 1.00, 1.25, and 1.50.

TABLE 2

Zoom ratio	D_7	D_{11}	D_{14}	D_{17}
1.00	0.395	0.005	0.277	0.234
1.25	0.189	0.030	0.479	0.214
1.50	0.040	0.043	0.735	0.093

As set forth in Table 3 below, the zoom lens of Embodiment 1 of the present invention satisfies all of Conditions (1) through (4) above based on a normalized focal length of the zoom lens being unity at the wide-angle end.

TABLE 3

Condition No.	Condition	Value
(1)	$-2.2 < F1 / F < -1.2$	-1.663
(2)	$0.6 < F2 / F < 1.1$	0.923
(3)	$-15.0 < F4 / F < -1.5$	-1.945
(4)	$0.7 < F5 / F < 1.2$	0.852

Figs. 3A - 3D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 1 at the wide-angle end with a zoom ratio of 1.00. As shown in these figures, the f-number at this zoom ratio is 2.04 and the half-field angle ω is 15.1°. Figs. 3E - 3H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 1 at an intermediate position with a zoom ratio of 1.25. As shown in these figures, the f-number at this zoom ratio is 2.29 and the half-field angle ω is 11.9°. Figs. 3I - 3L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 1 at the telephoto end with a zoom ratio of 1.50. As shown in these figures, the f-number at this zoom ratio is 2.58 and the half-field angle ω is 9.9°. In Figs. 3A, 3E, and 3I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 486.1 nm (the F-line), and 656.3 nm (the C-line). In the remaining figures, ω is the half-field angle. In Figs. 3B, 3F and 3J, the astigmatism is shown for both the sagittal image surface S and the tangential image surface T. In Figs. 3C, 3G and 3K, distortion is measured at 587.6 nm (the d-line). In Figs. 3D, 3H and 3L, the lateral color is shown for the wavelengths 486.1 nm (the F-line) and 656.3 nm (the C-line) relative to 587.6 nm (the d-line). Unless otherwise noted, the aberrations are in mm. As is apparent from Figs. 3A - 3L, along with Tables 1 - 3, the zoom lens according to Embodiment 1 provides favorable correction of aberrations over the entire range of zoom, includes a suitable back focus distance, is nearly telecentric on the reducing side, and also provides a desirable balance of features of image brightness, compactness, and zoom ratio.

Embodiment 2

Fig. 2 shows the basic lens element configuration of the zoom lens of Embodiment 2. Embodiment 2 is similar to Embodiment 1 in that lens groups G_1 and G_5 remain stationary while lens groups G_2, G_3, and G_4 move during zooming adjustment. Embodiment 2 differs from

5   Embodiment 1 in its lens elements configuration by different radii of curvature of the lens surfaces, some different optical element surface spacings, and some different indexes of refraction of the lens element materials. Additionally, Embodiment 2 differs from Embodiment 1 in that the first lens group from the enlarging side, G_1, includes, in order from the enlarging side, a first lens element L_1 that is a plano-convex lens element with its convex surface on the

10   enlarging side, a second lens element L_2 that is a biconcave lens element having surfaces of different curvature and with its surface of greater curvature on the reducing side, a third lens element L_3 that is a biconcave lens element having surfaces of different curvature and with its surface of greater curvature on the enlarging side, and a fourth lens element L_4 that is a biconvex lens element having surfaces of different curvature and with its surface of greater curvature on

15   the enlarging side.

Table 4 below lists the surface number #, in order from the enlarging side, the radius of curvature R of each surface, the on-axis surface spacing D, as well as the refractive index N_d and the Abbe number v_d (both at the d-line) of each lens element for Embodiment 2. The numerical values of R and D are based on a normalized focal length being unity at the wide-angle end

20   configuration of the zoom lens of Embodiment 2 (i.e., with the zoom lens focused at infinity). The zoom lens of Embodiment 2 provides a reducing magnification of -0.0098 at the image reducing side at the wide-angle end of the zoom lens.

TABLE 4

#	R	D	N_d	v_d
1	1.892	0.109	1.83400	37.2
2	∞	0.291		
3	-17.355	0.041	1.49700	81.5
4	0.724	0.114		
5	-1.295	0.038	1.72047	34.7
6	1.408	0.100		
7	2.005	0.061	1.83400	37.2
8	-15.046	D_8 (variable)		
9	2.084	0.107	1.72916	54.7
10	-2.084	0.148		
11	0.892	0.066	1.80400	46.6
12	3.452	D_{12} (variable)		
13	0.871	0.123	1.61800	63.3
14	-1.544	0.032	1.69895	30.1
15	0.529	D_{15} (variable)		
16	-1.593	0.029	1.56384	60.7
17	0.737	0.067	1.80100	39.5
18	5.369	D_{18} (variable)		
19	-0.848	0.035	1.68893	31.1
20	2.068	0.035		
21	-4.715	0.077	1.77250	49.6
22	-0.932	0.004		
23	1.430	0.097	1.80400	46.6
24	-3.025	0.154		
25	1.226	0.090	1.60311	60.6
26	∞	0.117		
27	∞	0.549	1.51633	64.1
28	∞			

In the zoom lens of Embodiment 2, lens groups G_2, G_3, and G_4 move to vary the separations of the five lens groups during zooming. Therefore, the values of the on-axis spacings D_8, D_{12}, D_{15} and D_{18} vary.

Table 5 below lists the values of the variables D_8, D_{12}, D_{15} and D_{18} (i.e., the group spacings) at zoom ratios of 1.00, 1.25, and 1.50.

TABLE 5

Zoom ratio	D_8	D_{12}	D_{15}	D_{18}
1.00	0.379	0.012	0.163	0.360
1.25	0.168	0.044	0.396	0.306
1.50	0.008	0.088	0.672	0.145

As set forth in Table 6 below, the zoom lens of Embodiment 2 of the present invention satisfies all of Conditions (1) through (4) above based on a normalized focal length of the zoom lens being unity at the wide-angle end.

TABLE 6

Condition No.	Condition	Value
(1)	$-2.2 < F1 / F < -1.2$	-1.630
(2)	$0.6 < F2 / F < 1.1$	0.775
(3)	$-15.0 < F4 / F < -1.5$	-5.547
(4)	$0.7 < F5 / F < 1.2$	0.976

Figs. 4A - 4D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 2 at the wide-angle end with a zoom ratio of 1.00. As shown in these figures, the f-number at this zoom ratio is 2.04 and the half-field angle ω is 15.0°. Figs. 4E - 4H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 2 at an intermediate position with a zoom ratio of 1.25. As shown in these figures, the f-number at this zoom ratio is 2.31 and the half-field angle ω is 11.9°. Figs. 4I - 4L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 2 at the telephoto end with a zoom ratio of 1.50. As shown in these figures, the f-number at this zoom ratio is 2.56 and the half-field angle ω is 10.0° In Figs. 4A, 4E, and 4I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 486.1 nm (the F-line), and 656.3 nm (the C-line). In the remaining figures, ω is the half-field angle. In Figs. 4B, 4F and 4J, the astigmatism is shown for both the sagittal image surface S and the tangential image surface T. In Figs. 4C, 4G and 4K, distortion is measured at 587.6 nm (the d-line). In Figs. 4D, 4H and 4L, the lateral color is shown for the wavelengths 486.1 nm (the F-line) and 656.3 nm (the C-line) relative to 587.6 nm (the d-line). Unless otherwise noted, the aberrations are in mm.

As is apparent from Figs. 4A - 4L, along with Tables 4 - 6, the zoom lens according to Embodiment 2 provides favorable correction of aberrations over the entire range of zoom, includes a suitable back focus distance, is nearly telecentric on the reducing side, and also provides a desirable balance of features of image brightness, compactness, and zoom ratio.

15

Embodiment 3

Embodiment 3 is similar to Embodiment 1. As in Embodiment 1, in Embodiment 3 lens groups G_1 and G_5 remain stationary while lens groups G_2, G_3, and G_4 move during zooming adjustment. However, in this embodiment, the fourth lens group G_4 at first moves toward the

5   enlarging side and then moves toward the reducing side during zooming from the wide-angle end to the telephoto end. Embodiment 3 also differs from Embodiment 1 in its lens element configuration by having different radii of curvature of the lens surfaces, some different optical element surface spacings, and some different indexes of refraction of the lens element materials. Additionally, Embodiment 3 differs from Embodiment 1 in that the first lens group from the

10   enlarging side, G_1, includes, in order from the enlarging side, a first lens element L_1 that is a meniscus lens element having positive refractive power and with its convex surface on the enlarging side, a second lens element L_2 that is a plano-concave lens element with its planar surface on the enlarging side, a third lens element L_3 that is a biconcave lens element having surfaces of different curvature and with its surface of greater curvature on the enlarging side, and

15   a fourth lens element L_4 that is a plano-convex lens element with its convex surface on the enlarging side.

Table 7 below lists the surface number #, in order from the enlarging side, the radius of curvature R of each surface, the on-axis surface spacing D, as well as the refractive index N_d and the Abbe number v_d (both at the d-line) of each lens element for Embodiment 3. The numerical

20   values of R and D are based on a normalized focal length being unity at the wide-angle end configuration of the zoom lens of Embodiment 3 (i.e., with the zoom lens focused at infinity). The zoom lens of Embodiment 3 provides a reducing magnification of -0.0098 at the image-reducing side at the wide-angle end of the zoom lens.

TABLE 7

#	R	D	N_d	ν_d
1	1.991	0.092	1.83400	37.2
2	16.980	0.241		
3	∞	0.041	1.49700	81.5
4	0.719	0.242		
5	-1.261	0.038	1.64769	33.8
6	2.826	0.050	1.83481	42.7
7	∞	D_7 (variable)		
8	2.265	0.105	1.75500	52.3
9	-2.265	0.157		
10	0.793	0.076	1.80400	46.6
11	3.239	D_{11} (variable)		
12	0.716	0.105	1.65160	58.6
13	-1.715	0.032	1.69895	30.1
14	0.434	D_{14} (variable)		
15	-1.305	0.029	1.65160	58.6
16	0.464	0.107	1.80100	39.5
17	-7.812	D_{17} (variable)		
18	-0.560	0.035	1.75520	25.7
19	6.234	0.021		
20	-4.621	0.103	1.80400	46.6
21	-0.693	0.004		
22	2.724	0.074	1.80400	46.6
23	-3.441	0.022		
24	1.059	0.154	1.61800	63.3
25	∞	0.117		
26	∞	0.550	1.51633	64.1
27	∞			

In the zoom lens of Embodiment 3, lens groups G_2, G_3, and G_4 move to vary the separations of the five lens groups during zooming. Therefore, the values of the on-axis spacings D_7, D_{11}, D_{14} and D_{17} vary.

Table 8 below lists the values of the variables D_7, D_{11}, D_{14} and D_{17} (i.e., the group spacings) at zoom ratios of 1.00, 1.20, and 1.40.

TABLE 8

Zoom ratio	D_7	D_{11}	D_{14}	D_{17}
1.00	0.419	0.004	0.168	0.417
1.20	0.251	0.033	0.303	0.422
1.40	0.117	0.077	0.425	0.390

As set forth in Table 9 below, the zoom lens of Embodiment 3 of the present invention

satisfies all of Conditions (1) through (4) above based on a normalized focal length of the zoom lens being unity at the wide-angle end.

TABLE 9

Condition No.	Condition	Value
(1)	$-2.2 < F1 / F < -1.2$	-1.526
(2)	$0.6 < F2 / F < 1.1$	0.742
(3)	$-15.0 < F4 / F < -1.5$	-14.268
(4)	$0.7 < F5 / F < 1.2$	1.042

Figs. 5A - 5D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 3 at the wide-angle end with a zoom ratio of 1.00. As shown in these figures, the f-number at this zoom ratio is 2.04 and the half-field angle ω is 15.0° Figs. 5E - 5H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 3 at an intermediate position with a zoom ratio of 1.20. As shown in these figures, the f-number at this zoom ratio is 2.23 and the half-field angle ω is 12.4° Figs. 5I - 5L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 3 at the telephoto end with a zoom ratio of 1.40. As shown in these figures, the f-number at this zoom ratio is 2.40 and the half-field angle ω is 10.6° In Figs. 5A, 5E, and 5I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 486.1 nm (the F-line), and 656.3 nm (the C-line). In the remaining figures, ω is the half-field angle. In Figs. 5B, 5F and 5J, the astigmatism is shown for both the sagittal image surface S and the tangential image surface T. In Figs. 5C, 5G and 5K, distortion is measured at 587.6 nm (the d-line). In Figs. 5D, 5H and 5L, the lateral color is shown for the wavelengths 486.1 nm (the F-line) and 656.3 nm (the C-line) relative to 587.6 nm (the d-line). Unless otherwise noted, the aberrations are in mm.

As is apparent from Figs. 5A - 5L, along with Tables 7 - 9, the zoom lens according to Embodiment 3 provides favorable correction of aberrations over the entire range of zoom, includes a suitable back focus distance, is nearly telecentric on the reducing side, and also provides a desirable balance of features of image brightness, compactness, and zoom ratio.

Embodiment 4

Embodiment 4 is similar to Embodiment 1. As in Embodiment 1, in Embodiment 4 lens groups G_1 and G_5 remain stationary while lens groups G_2, G_3, and G_4 move during zooming adjustment. Embodiment 4 differs from Embodiment 1 in its lens element configuration by

5   different radii of curvature of the lens surfaces, some different optical element surface spacings, and some different indexes of refraction of the lens element materials. Additionally, Embodiment 4 differs from Embodiment 1 in that none of the lens groups G_1 through G_5 includes intimately bonded lens elements, that is, for example, lens elements cemented together. Rather, each lens component of Embodiment 4 is a lens element.

10   Table 10 below lists the surface number #, in order from the enlarging side, the radius of curvature R of each surface, the on-axis surface spacing D, as well as the refractive index N_d and the Abbe number v_d (both at the d-line) of each lens element for Embodiment 4. The numerical values of R and D are based on a normalized focal length being unity at the wide-angle end configuration of the zoom lens of Embodiment 4 (i.e., with the zoom lens focused at infinity).

15   The zoom lens of Embodiment 4 provides a reducing magnification of -0.0098 at the image-reducing side at the wide-angle end of the zoom lens.

TABLE 10

#	R	D	N_d	v_d
1	1.777	0.115	1.83400	37.2
2	-184.771	0.259		
3	21.826	0.041	1.49700	81.5
4	0.777	0.105		
5	-1.600	0.038	1.75520	27.5
6	1.140	0.109		
7	1.644	0.058	1.84666	23.8
8	10.341	D_8 (variable)		
9	2.337	0.069	1.72916	54.7
10	-2.630	0.171		
11	0.900	0.067	1.77250	49.6
12	4.016	D_{12} (variable)		
13	0.851	0.112	1.69680	55.5
14	-2.875	0.015		
15	-2.289	0.032	1.69895	30.1
16	0.520	D_{16} (variable)		
17	-1.347	0.029	1.48749	70.2
18	0.756	0.015		
19	0.792	0.062	1.80100	39.5
20	2.527	D_{20} (variable)		
21	-1.391	0.035	1.76182	26.5
22	1.850	0.028		
23	74.750	0.078	1.77250	49.6
24	-1.128	0.004		
25	1.378	0.089	1.80400	46.6
26	-4.814	0.223		
27	1.199	0.098	1.62041	60.3
28	∞	0.117		
29	∞	0.549	1.51633	64.1
30	∞	0.024		
31	∞			

In the zoom lens of Embodiment 4, lens groups G_2, G_3, and G_4 move to vary the separations of the five lens groups during zooming. Therefore, the values of the on-axis spacings D_8, D_{12}, D_{16}, and D_{20} vary.

Table 11 below lists the values of the variables D_8, D_{12}, D_{16} and D_{20} (i.e., the group spacings) at zoom ratios of 1.00, 1.20, and 1.40.

TABLE 11

Zoom ratio	D_8	D_{12}	D_{16}	D_{20}
1.00	0.388	0.009	0.169	0.312
1.20	0.213	0.031	0.375	0.257
1.40	0.077	0.064	0.580	0.156

As set forth in Table 12 below, the zoom lens of Embodiment 4 of the present invention satisfies all of Conditions (1) through (4) above based on a normalized focal length of the zoom lens being unity at the wide-angle end.

TABLE 12

Condition No.	Condition	Value
(1)	$-2.2 < F1 / F < -1.2$	-1.709
(2)	$0.6 < F2 / F < 1.1$	0.843
(3)	$-15.0 < F4 / F < -1.5$	-3.307
(4)	$0.7 < F5 / F < 1.2$	0.931

Figs. 6A - 6D show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 4 at the wide-angle end with a zoom ratio of 1.00. As shown in these figures, the f-number at this zoom ratio is 2.04 and the half-field angle ω is 15.0° Figs. 6E - 6H show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 4 at an intermediate position with a zoom ratio of 1.20. As shown in these figures, the f-number at this zoom ratio is 2.24 and the half-field angle ω is 12.5° Figs. 6I - 6L show the spherical aberration, astigmatism, distortion, and lateral color, respectively, of the zoom lens of Embodiment 4 at the telephoto end with a zoom ratio of 1.40. As shown in these figures, the f-number at this zoom ratio is 2.42 and the half-field angle ω is 10.7° In Figs. 6A, 6E, and 6I, the spherical aberration is shown for the wavelengths 587.6 nm (the d-line), 486.1 nm (the F-line), and 656.3 nm (the C-line). In the remaining figures, ω is the half-field angle. In Figs. 6B, 6F and 6J, the astigmatism is shown for both the sagittal image surface S and the tangential image surface T. In Figs. 6C, 6G and 6K, distortion is measured at 587.6 nm (the d-line). In Figs. 6D, 6H and 6L, the lateral color is shown for the wavelengths 486.1 nm (the F-line) and 656.3 nm (the C-line) relative to 587.6 nm (the d-line). Unless otherwise noted, the aberrations are in mm.

As is apparent from Figs. 6A - 6L, along with Tables 10 - 12, the zoom lens according to

Embodiment 4 provides favorable correction of aberrations over the entire range of zoom, includes a suitable back focus distance, is nearly telecentric on the reducing side, and also provides a desirable balance of features of image brightness, compactness, and zoom ratio.

A projection display device of the present invention may use the zoom lens of the present invention in combination with a light source and an image source as a projection lens in order to project onto a screen an optical image created by light from the light source that is modulated by the image source. For example, in the case of a liquid crystal display device being arranged relative to the zoom lens as shown in Fig. 1, a nearly parallel luminous flux enters from the liquid crystal display device from the right side of Fig. 1. The luminous flux is modulated using image information supplied to the liquid crystal display panel 1 and is then transmitted by the glass block 2 and the lens elements of the zoom lens in order to project a magnified image onto a screen (not shown) positioned to the left of Fig. 1. Additionally, similarly to liquid crystal video projectors in general, a full color image may be projected by separating the luminous flux emitted from the light source into three primary colors of red, blue, and green with a color separation optical system such as a dichroic prism and a lens array passing each primary color through a separate one of three liquid crystal display elements, and synthesizing the three colors into a single light beam with a color synthesizing optical system, such as a dichroic prism, represented by the glass block 2 shown in Fig. 1.

An example of a projection display device in which a zoom lens of the present invention may be used is shown schematically in Fig. 7. As shown in Fig. 7, the projection display device includes a light source 101 that projects collimated light to a color separation optical system 102 that divides the light into red (R), green (G), and blue (B) light beams. The red, green, and blue light beams are separately modulated by modulators, such as transmission liquid crystal display elements 103, 104, and 105, that modulate the light in order to provide image information of different colors and are transmitted to the zoom lens 106 of the present invention operating as a projection lens. The zoom lens 106 includes a color synthesizing optical system 107 that combines the modulated red, blue, and green light beams into a single colored light beam for focusing by a zooming lens portion 108 that projects the combined color modulated light beam onto a screen 109. The color separation optical system 102 may include a dichroic prism and a

lens array and the color synthesizing optical system may also be a dichroic prism.

In a projection display device, if the projection display device is designed so that the lens may be exchanged, the user can change the lens so that the position of the projection display device can be selected freely. The zoom lens of the present invention may thus replace a standard zoom lens having a standard projection distance so as to enable the projection display device of the present invention to project an image of high optical quality from positions that may be freely selected.

The present invention is not limited to the aforementioned embodiments, as it will be obvious that various alternative implementations are possible. For instance, the number of lens elements and lens components in each lens group may be varied. Additionally, values such as the radius of curvature R of each of the lens elements and components, the surface spacings D, the refractive index N_d, as well as the Abbe number ν_d, are not limited to the examples indicated in each of the aforementioned embodiments, as other values can be adopted. Furthermore, the zoom lens according to the present invention is not limited to the form used as the projection lens of a projection display device that uses transmission of liquid crystal display elements but may be used as a projection lens for devices that use other light modulation means, such as reflection liquid crystal display elements or DMD's. Additionally, the zoom lens of the present invention may be used as an image forming lens in a camera, such as a camera using a camera tube, a CCD, or photographic film. Such variations are not to be regarded as a departure from the spirit and scope of the invention. Rather, the scope of the invention shall be defined as set forth in the following claims and their legal equivalents. All such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.